Exoplanet Community Report: Direct Optical Imaging of Exoplanets

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Context

- TPF STDT & TPF Technology Plan: Extensive requirements to discover and characterize terrestrial planets in the HZ - Large Flagship many $B
- Exoplanet Task Force (ExoPTF): focus on big picture strategy, ordering of missions, focus on habitable planet characterization
- NASA Concept Mission Studies, several on direct optical imaging
- Exoplanet Forum May 2008

- Task for our chapter on Direct optical imaging:
  - Provide an update on direct imaging science
  - Study the case of a probe (medium) size mission
  - Provide a technology assessment for both coronagraphs and occulters

Chapter summary

- Science goals summary
  - Large missions: Earth twin template
  - Medium missions: Giants planets, Neptunes, Super Earths, disks.
  - Discussion of combined astrometric or RV detection with imaging
- Architecture scaling
  - Relevant scales for direct imaging
  - Two types of architecture: Internal coronagraphs and external occulters
- Technology
  - Specific technologies for internal and external architectures
  - Shared technologies

Chapter summary

Large missions

- ExoPTF recommendation:
  - Astrometry provides mass and orbits
  - Astrometric precursor can provide ‘Where’ and ‘When’ to observe with the followup characterization mission

- Revisit the ExoPTF recommendation:
  - Precursor astrometric mission and characterization must be matched
  - ‘Where’: precursor information for direct imaging missions?
  - ‘When’: ephemeris accuracy for imaging missions?

Medium missions

ExoPTF Report: "While our Task Force fully appreciates the great scientific potential for characterizing extrasolar giant planets from space, we recognize that this capability may not lie on the critical path to directly detecting and characterizing extrasolar terrestrial planets. **Any mission that will accomplish our primary goal will (if properly defined) also characterize numerous giant planets.** We thus do not call specifically for a cool giant planet characterization mission. However if technological innovation enables an inexpensive new approach, or if a mission specifically designed to detect such planets turns out to lie on the critical path to characterization of Earths, we would enthusiastically await its discoveries."

However, ExoPTF also says that the knowledge of exozodiacal disks is on the critical path.

Medium missions

- Expand the ExoPTF recommendation of combining indirect and direct methods to a medium size mission:
  - Combine RV & ground-based astrometry with a characterizer mission
- Solve the exozodical dust question for future flagship mission

- This strategy is independent of an astrometric mission both in terms of science goals and timing sequence

Large mission: TPF-C requirements (STDT)

5) TPF-C shall be able to detect photons within the spectral range from **0.5 μm to 1.1 μm**.

(6) TPF-C shall be able to measure the **absolute brightness** of the Earth twin planet in Requirement (1) in at least one bandpass to within 10%.

(7) For the Earth and Jupiter twins in Requirements (1, 2), TPF-C shall be able to measure the **relative brightness** in at least three broad spectral bands to a relative accuracy of 10% or better.

(8) TPF-C shall be able to **detect O_2 and H_2O** in the atmosphere of the Earth twin planet specified in Requirement (1). Relevant absorption bands and required resolutions are listed in 1.4.1. TPF-C shall also be able to **detect CH_4** in the atmosphere of a Jupiter twin in this same system. Detection is defined as the ability to measure the equivalent width of a spectral band to within 20% accuracy.

(9) TPF-C shall have a minimum **spectral resolution of 70** over the entire bandpass specified in requirement (5) to allow the mission to search for absorption bands of unspecified gases or surface minerals.

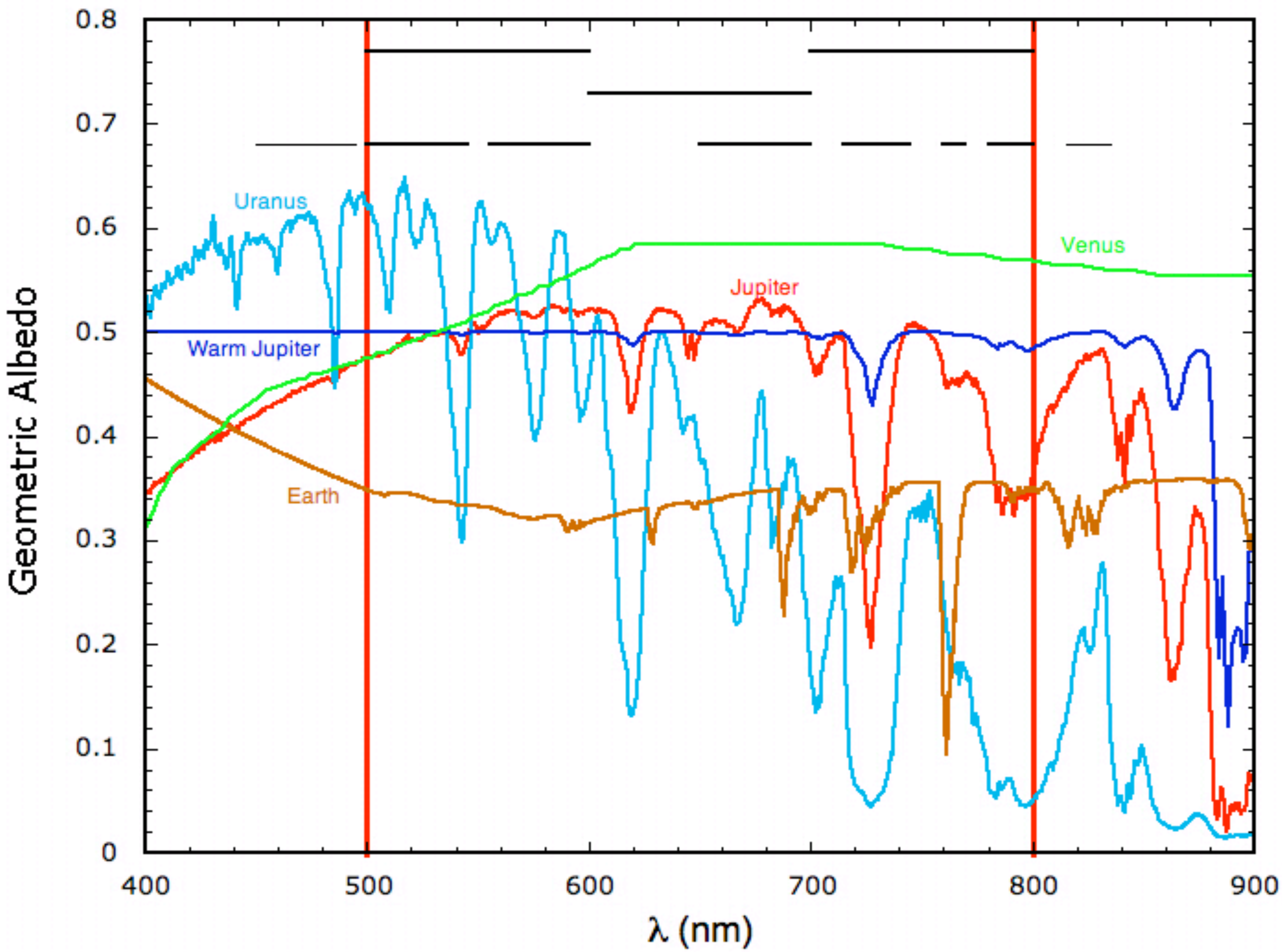
IWA - OWA

65 - 500 mas

Direct imaging main goals for a small mission

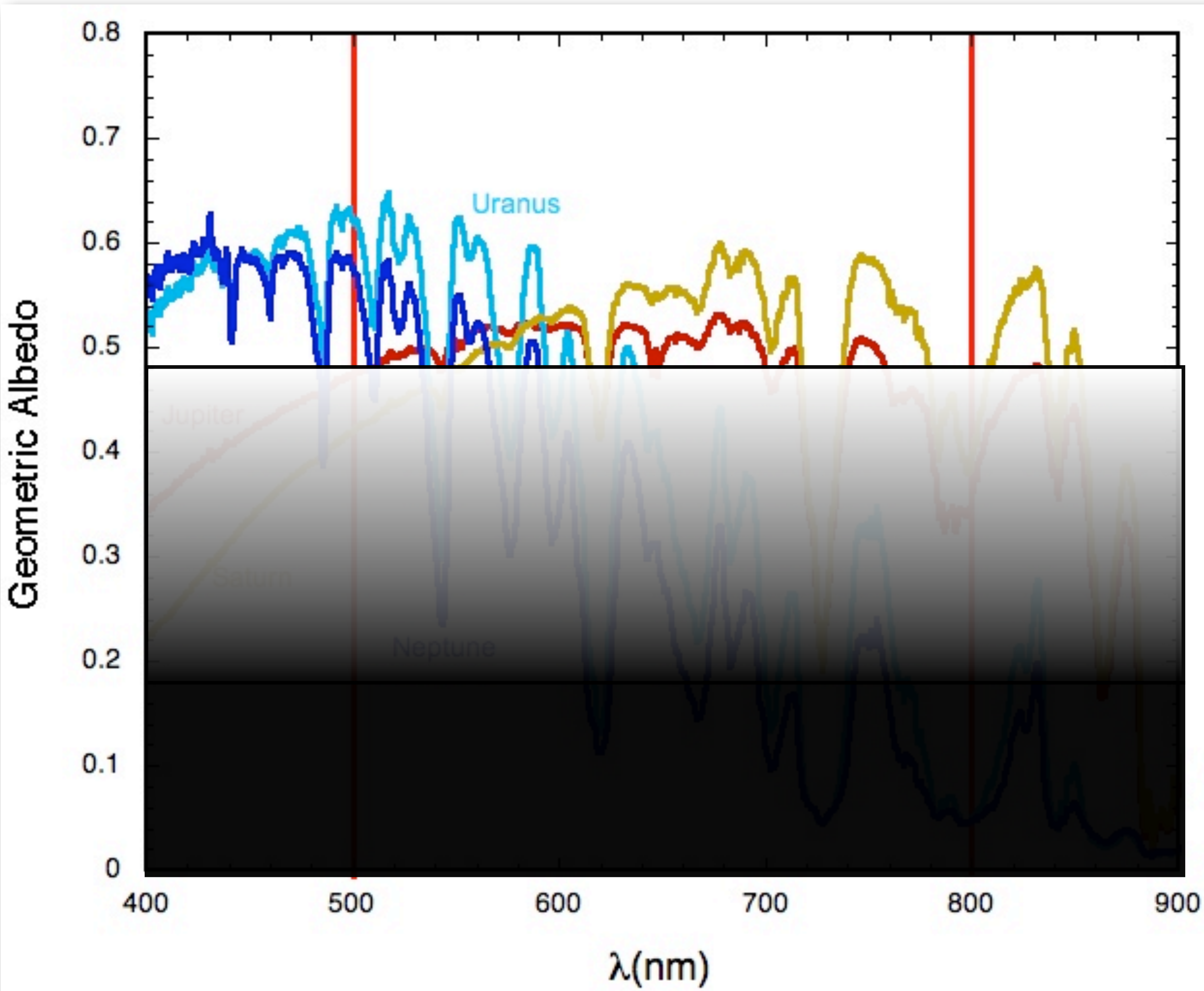
- Giants, Neptune-mass, Super Earths
- Observations of known RV planets (and planets to be detected by ground based Astrometry)
  - constrain orbital inclination and thus the mass (2 observations at least)
- Obtain low-resolution spectra or filter spectroscopy to characterize the slope and band depths of the major absorbers
  - constraints on atmospheric temperature, presence of bright cloud layers, system age, mass of the planet
- Determination of the atmospheric composition to infer whether the pattern of enrichment seen in solar system giants holds in other systems as well
  - the utility of low resolution, low SNR spectra needs to be studied

Spectra and possible filters



Marley et al.

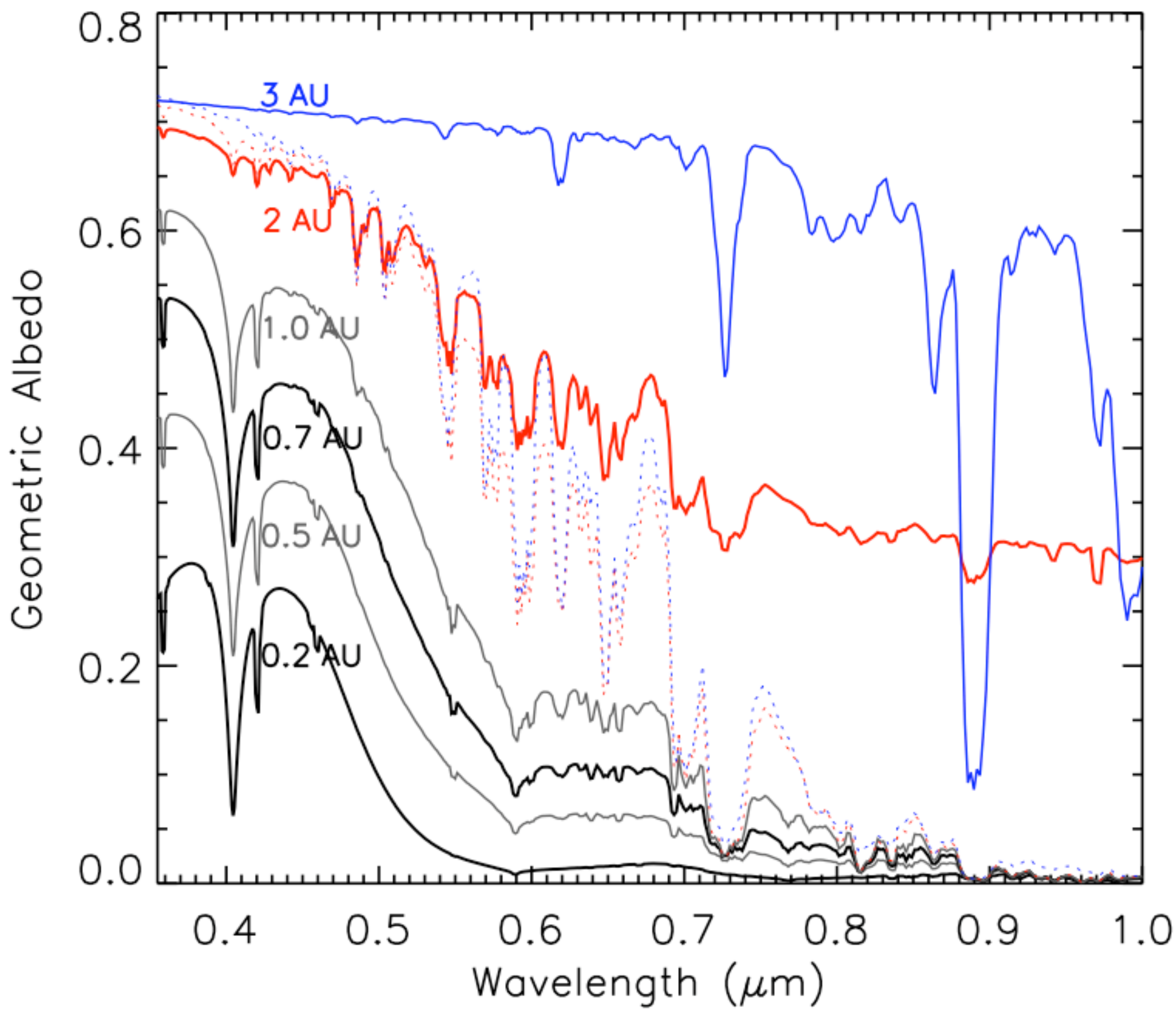
Continuum alone is not enough



- Information is in the band depths
- Just detecting continuum with dropouts limits interpretation

Marley et al.

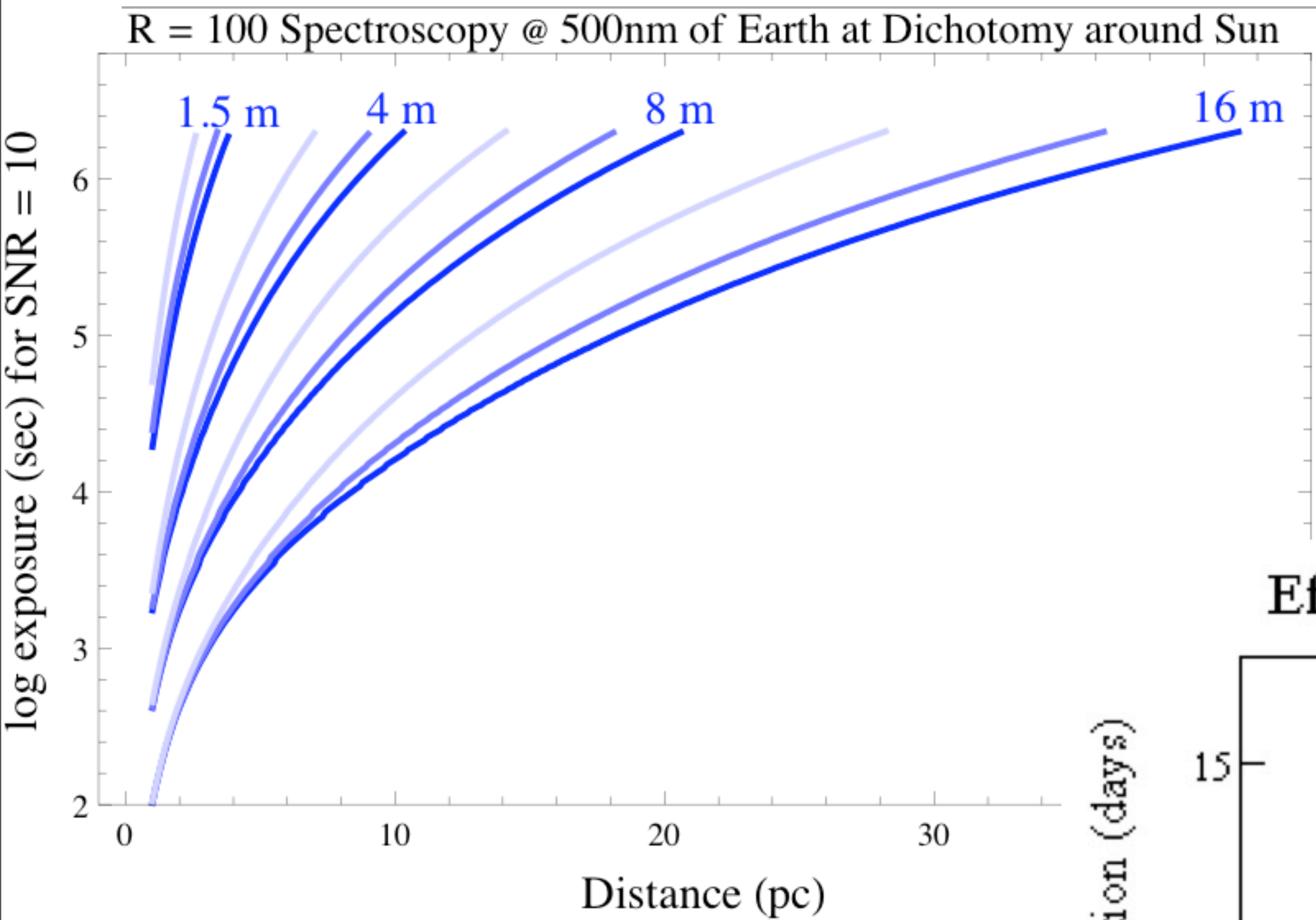
Not all "Jupiters" are "Jupiter"

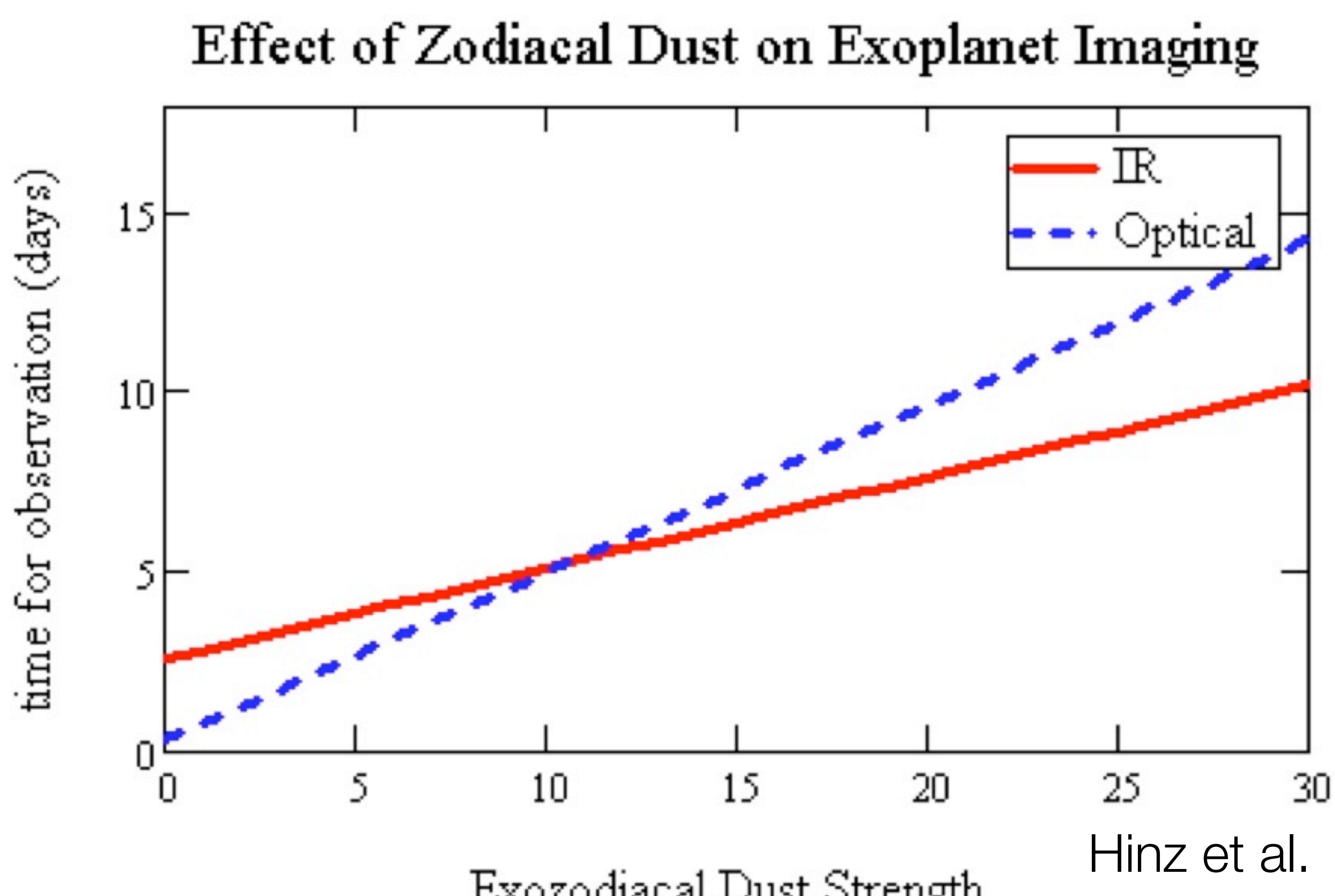


- "Jupiter" at various orbital distance
- Spectral shape - continuum/band contrast - yields temperature range
- Constrains gravity and albedo

Fortney et al.

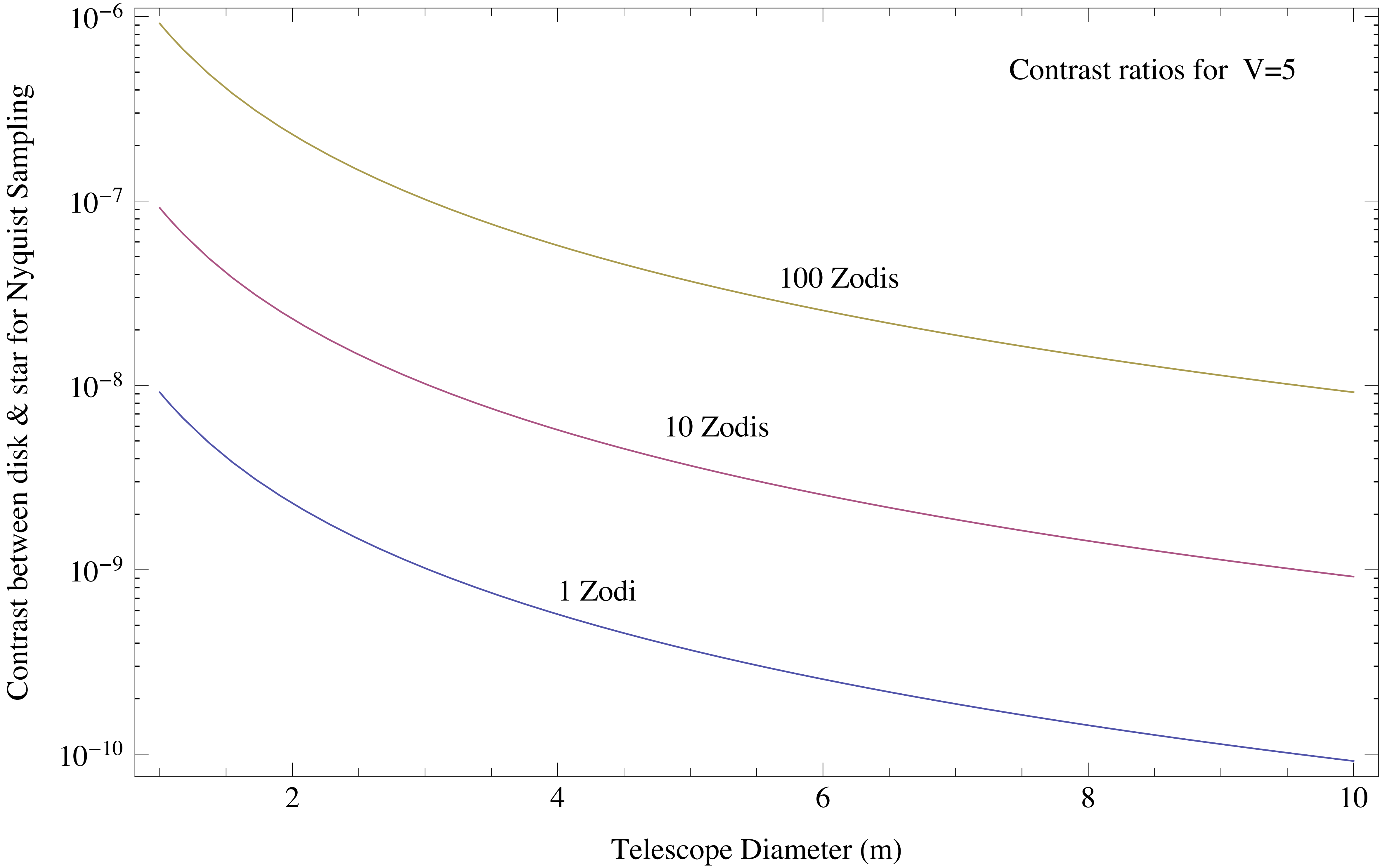
Limitations from ExoZodiacal Disk





Hinz et al.

Exozodi imaging



Planet characterization

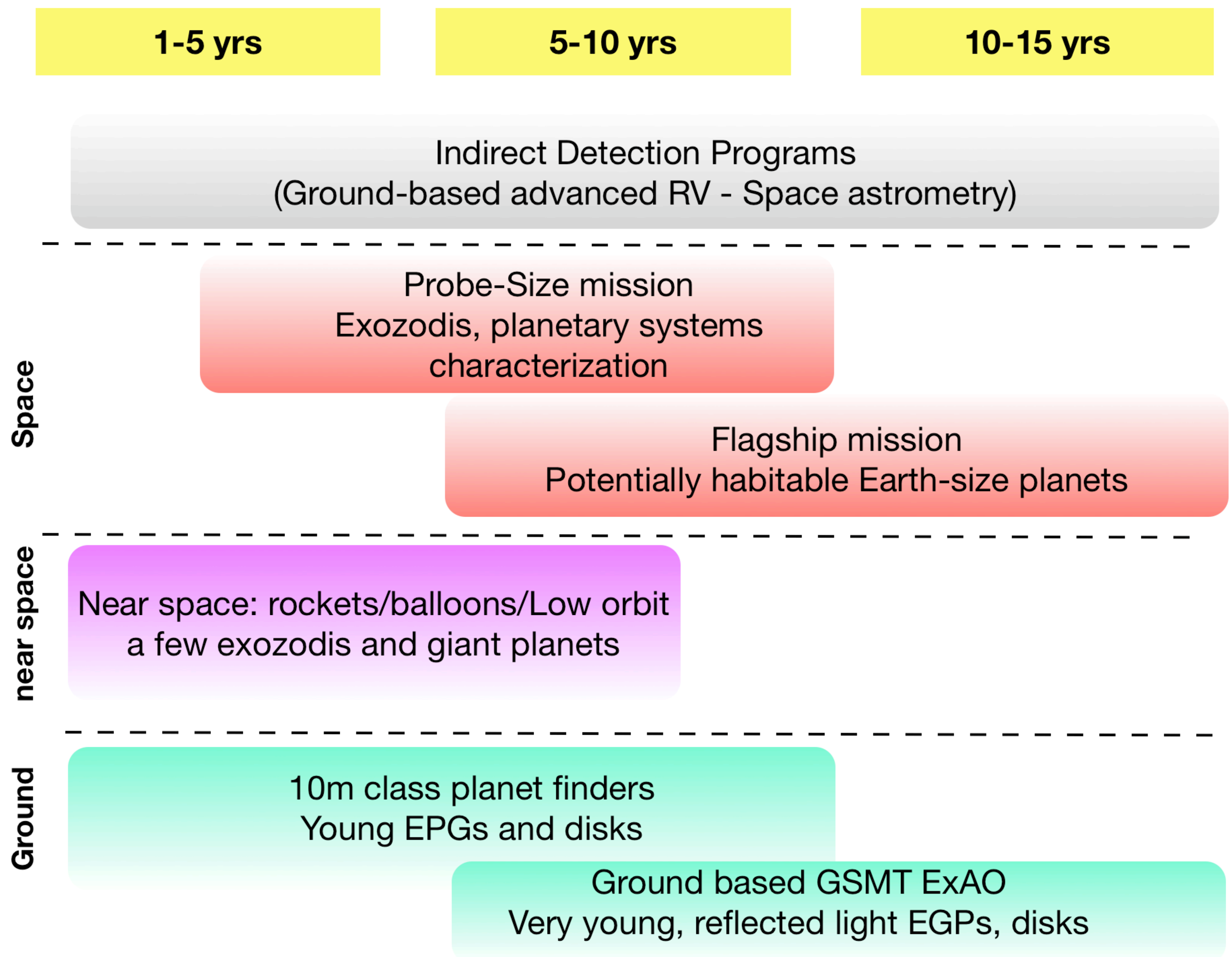
- *Avoid:* pale blue dot, *no* mass, *no* radius, *no* spectrum
- Spectra may be challenging for small mission
- Photometric estimates unreliable
  - Clouds, photochemistry, surface composition, more variety than we can anticipate, many degenerate interpretations
- Spectral gravity indicators plausible, but:
  - model dependent, radius, mass, composition degeneracies
  - challenging at low S/N, low R

- Need RV and/or astrometric detection for complete characterization
  - in principle 2 images yield mass for RV planets
  - need to model accuracy given realistic mission
  - fiducial objects allow characterization of other worlds

Relevant architecture scales

- Coronagraphs
  - Ground-based telescopes (ExAO current & ELTs)
  - Suborbital environments (balloons & sounding rockets)
  - Probe/medium size missions (~$700M)
  - Flagship missions (>$1B)
- Occulters
  - Flagship
  - Probe if ‘host telescope’ used, e.g. JWST
- Hybrid systems
  - Flagship

Relevant architecture scales



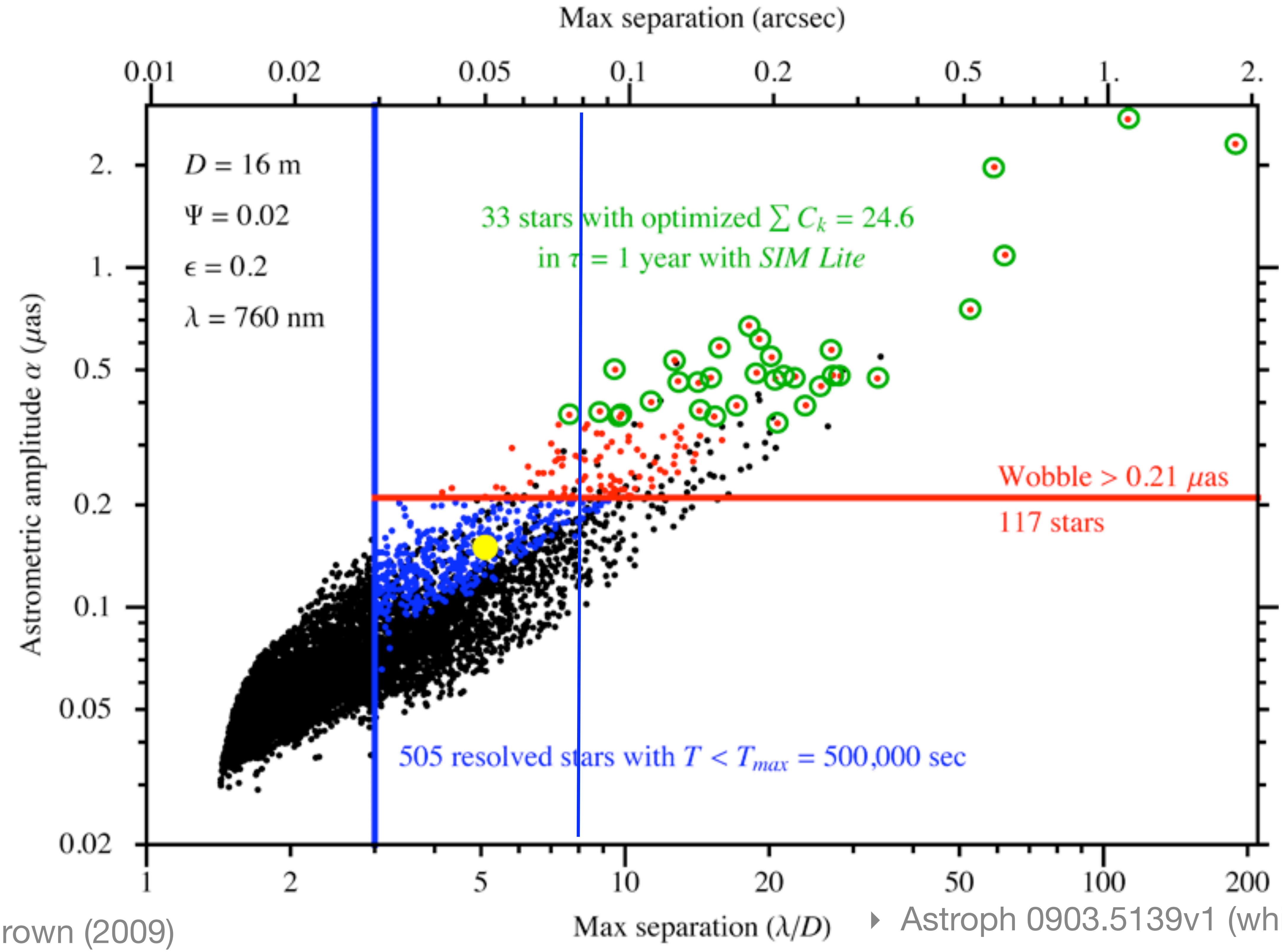
Note: boxes start with beginning of mission development

Astrometry and Imaging

- Combination of indirect & direct methods is necessary to provide full characterization
  - Both missions need to be matched
  - Mass is biased from astrometry measurements (Brown 2009)

- ExoPTF: astrometry provides the ‘Where’ & ‘When’ to observe
- ‘Where’
  - Little gain from precursor knowledge based on DRM study for occulter and coronagraph (Savransky et al. 2009)
- ‘When’
  - low completeness of recovery based on astrometric ephemeris (Brown 2009)

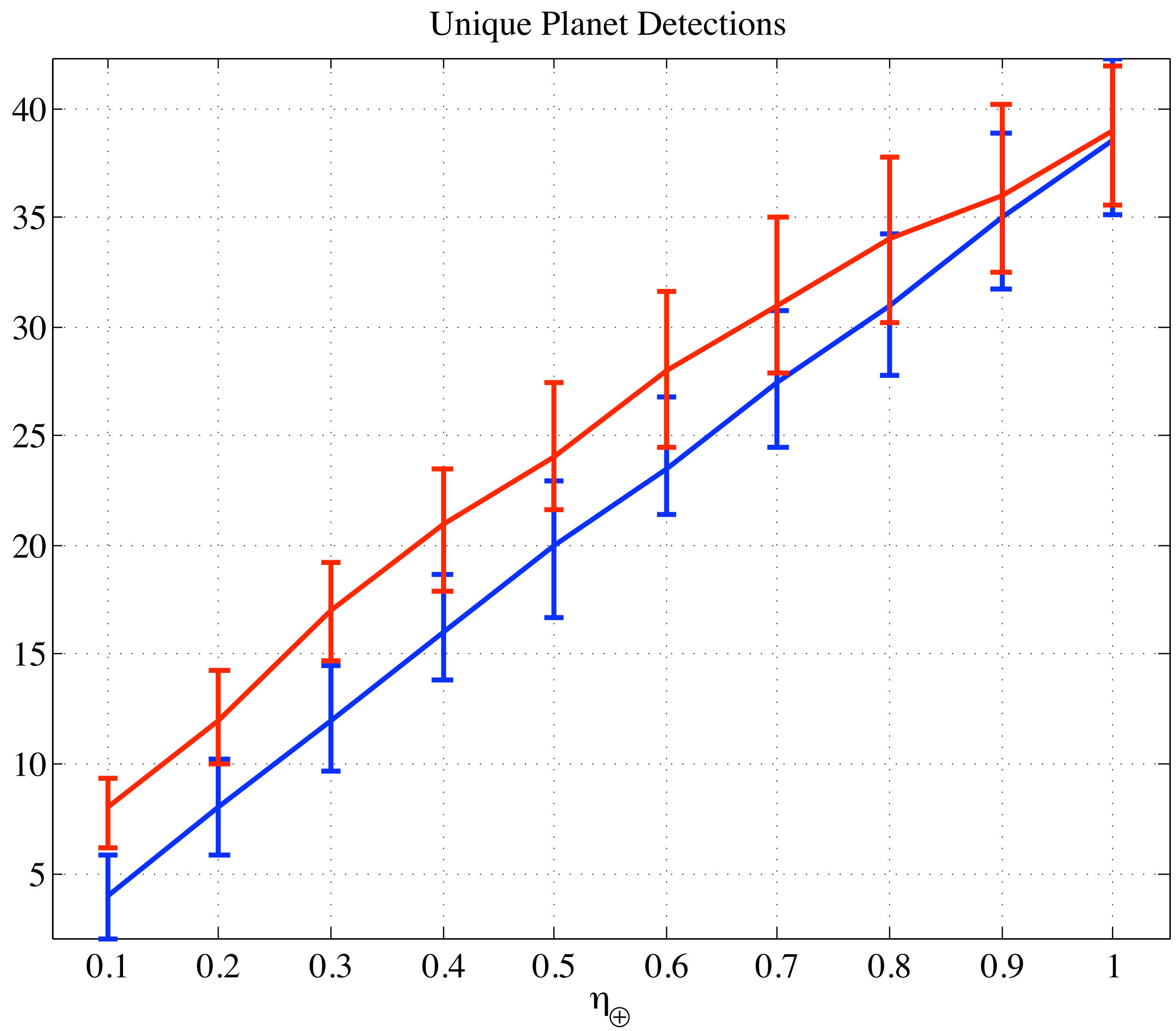
Matching Astrometry and Direct Optical Imaging

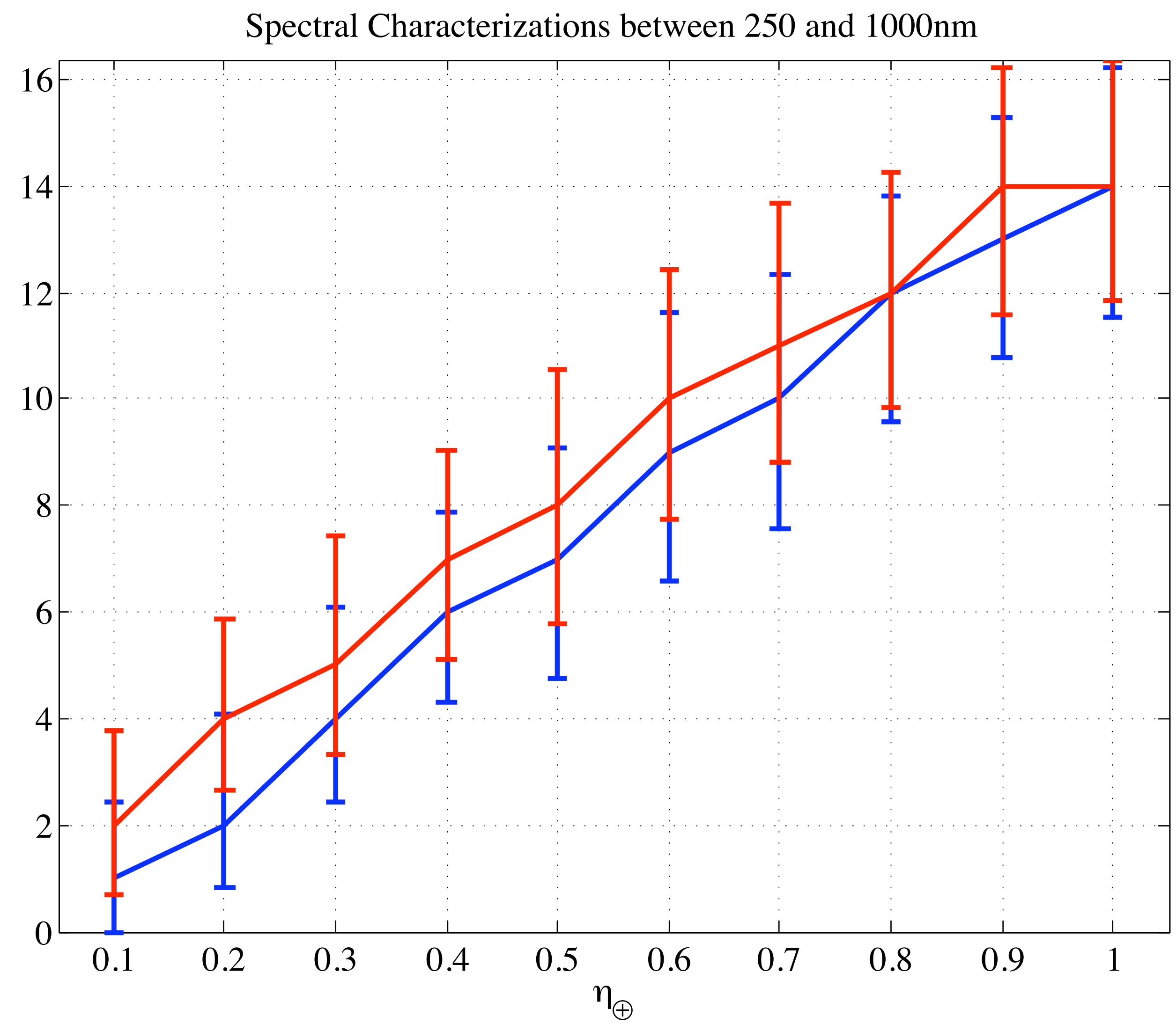


- Bob Brown (2009)
- Astroph 0903.5139v1 (white paper)

Precursor knowledge

- Little gain in detections and characterizations
- Gain in exposure time available for general astrophysics

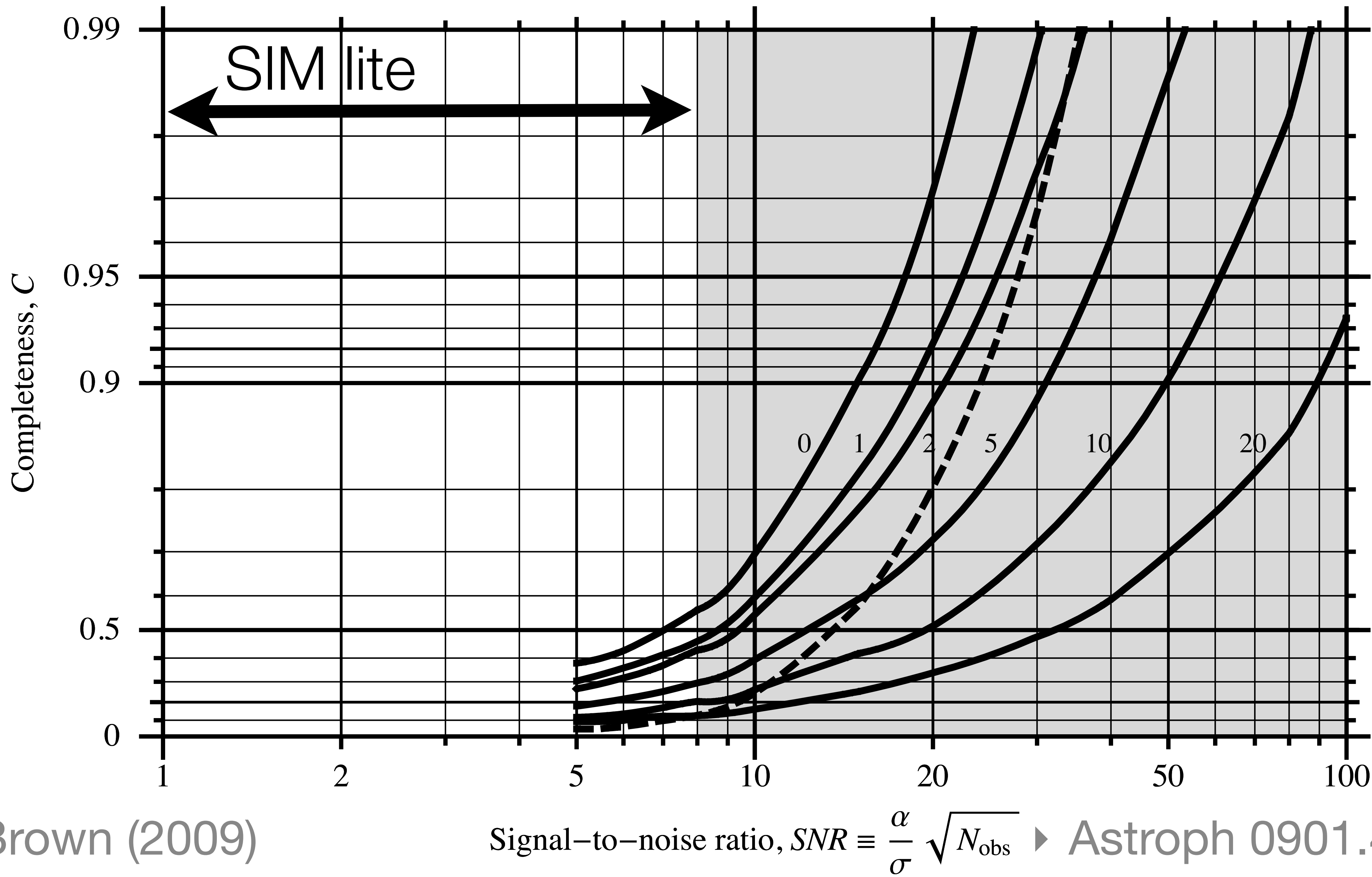




- Savransky, Kasdin & Cady 2009
  - Astroph 0903.4915 (submitted)

Precursor knowledge

- positional metric +/- 0.3 a, C=0.5 after 1 year, C=0.3 after 5 years (SNR=8)
- recovery completeness C<0.1 after one period after end of astrometric observations



- Bob Brown (2009)
- Astroph 0901.4897v2 (ApJ)

Overlap with RV planets

Planet Name	M sin i	Period (d)	a (AU)	sep``	Contrast (10^{-9})
Epsilon Eridani b	1.55	2502	3.39	1.06	1.6
55 Cnc d	3.84	5218	5.77	0.43	0.6
HD 160691 c	3.10	2986	4.17	0.27	1.1
Gj 849 b	0.82	1890	2.35	0.27	3.3
HD 190360 b	1.50	2891	3.92	0.25	1.2
47 Uma c	0.46	2190	3.39	0.24	1.6
HD 154345 b	0.95	3340	4.19	0.23	1.0
Ups And d	3.95	1275	2.51	0.19	2.9
Gamma Cephei b	1.60	903	2.044	0.17	4.4
HD 62509 b	2.90	590	1.69	0.16	6.4
HD 39091 b	10.35	2064	3.29	0.16	1.7
14 Her b	4.64	1773	2.77	0.15	2.4
47 Uma b	2.60	1083	2.11	0.15	4.1
HD 89307 b	2.73	3090	4.15	0.13	1.1
HD 10647 b	0.91	1040	2.1	0.12	4.2
HD 217107 c	2.50	3352	4.41	0.12	0.9
HD 117207 b	2.06	2627	3.78	0.12	1.3
HD 70642 b	2.00	2231	3.3	0.11	1.7
HD 128311 c	3.21	919	1.76	0.11	5.9

1.5m, 4λ/D @ 500nm

1.5m, 3λ/D @ 500nm

1.5m, 2λ/D @ 500nm

Overlap with RV planets

Planet Name	M sin i	Period (d)	a (AU)	sep``	Contrast (10^{-9})
Epsilon Eridani b	1.55	2502	3.39	1.06	1.6
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Occulter

Internal Coronagraph		1.5m Telescope @ 4λ/D	1.5m Telescope @ 2λ/D	4m Telescope @ 4λ/D	8m Telescope @ 4λ/D	16m Active Segmented @ 4λ/D
Coronagraph Instrument Technologies	Raw Contrast at IWA	$1e^{-10}$ @ 10-20% bandwidth	$1e^{-10}$ @ 10-20% bandwidth	$1e^{-10}$ @ 10-20% bandwidth	$1e^{-10}$ @ 10-20% bandwidth	$1e^{-10}$ @ 10-20% bandwidth
	DMs					
	WFSC Algorithms					
	Masks/Optics					
Telescope & Primary Mirror Technology						
Modeling Tools & Validation	Optical					
	Integrated: Opto-Thermal Mechanical					
Telescope Pointing		5-10 mas	< 5 mas	5-10 mas	10 mas	
Thermal Stability		<mK	~0.1mK	<mK	0.5 mK	
Detectors						
System Verification &						

External Coronagraph		1.1 m Telescope w/15 m Starshade	Existing Telescope w/ 50m Starshade	4m Telescope w/ 50m Starshade
Occulter Raw Contrast		$1e^{-8}$ @ 100% bandwidth	$1e^{-10}$ @ 100% bandwidth	$1e^{-10}$ @ 100% bandwidth
Occulter Deployment & Tolerance	Petal Position Errors	0.5 m	0.1 m	0.1 m
	Shape Error	5 mm	~10μm	~10μm
	Edge Effects	~1 cm	<1 mm	<1 mm
Telescope & Mirror Technology				
Modeling Tools & Validation	Optical & Scaling			
	Integrated Opto-Thermal Mechanical			
Formation Flying		±1 m	<1 m	<1 m
Occulter Thermal Control		~5 K	~5 K	~ 5 K
Detectors				
System Verification &				

Internal Coronagraph Technology

- Coronagraph concepts: Pupil apodization, Lyot Coronagraphs, Interferometric coronagraphs, other techniques
- Optical Diffraction modeling and laboratory demonstration
- Deformable mirrors
- Wavefront sensing and control algorithms (architecture, Control, Estimation)
- Coronagraph Optics manufacturing (binary masks, amplitude masks, phase masks, aspheric surface polishing)

External Occultor Technology

- Optical Diffraction Modeling and Laboratory Demonstration
- Occulter System Maturation
- Deployment
- Formation Flying & Pointing Control subsystem
- Precision edge and scattered sun light
- Integrated optical mechanical and thermal analysis
- Micrometeoroids
- Propulsion systems

Shared Technologies (Coronagraph & Occulter)

- Telescope and mirror technology (on/off -axis, Passive/Active, mirror quality, size
- Detectors (Photon Counting CCDs, Low Temperature Detectors
- Precision Thermal Control and Analysis
- Isolation Systems (Disturbance Free Payload, Two-stage isolation systems)
- Verification and Validation

Direct Optical Imaging: Executive summary

- Probe - scale mission for exoplanetary systems characterization that is not accessible from the ground in the same time frame
    - Exozodiacal characterization (1 zodi at 1-3 AU) of brightness, structures and clumpiness.
    - Direct detection and spectral characterization (0.4 to 1.0 um) of planets and planetary systems including at least 13 known RV Giant planets, and unknown Neptune-mass and Super Earths planets
- Long term flagship mission for the characterization of potentially habitable Earth-size planets
- Aggressive and sustained technology development starting immediately to meet readiness by mission start, including sub-orbital environments
- R&A support for developing preliminary science and maturing mission designs in particular for the definition and optimization of combined Astrometry/RV and imaging missions.

references

- Brown 2009
  - Astroph 0901.4897v2 (accepted in ApJ)
  - Astroph 0903.5139v1 (white paper)
- Savransky, Kasdin & Cady 2009
  - Astroph 0903.4915 (submitted)